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Physics-Based Scenario Modeling for Earthquake-Soil-Structure Interaction of Buildings

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Abstract

To this date, earthquake-soil-structure interaction (ESSI) studies have used detailed models of near surface geology (Yang et al., 2003; Jeremić et al., 2012), with input motions such as planar incident waves or scaled recorded ground motions. There has been no direct inclusion of physics-based finite fault synthetic ground motion in ESSI study cases which simultaneously include nonlinear site and structural response.

Ideally a complete ESSI model should include the following: (a) physical model of the source rupture process, (b) propagation of waves through the heterogeneous crust, (c) nonlinear site response, and (d) a detailed structural model of the infrastructure of interest. The domain reduction method (DRM, Yoshimura et al., 2003) reduces the computational demand by replacing the wave propagation inside the crust to only a small neighborhood of interest around the structure, and by applying consistent forces as boundary conditions. These forces are computed from the predicted earthquake wave field, which can be obtained using any method that solves the wave equation at a coarser resolution.

Presented is a method which (i) uses the UCSB broadband ground motion simulation method (Schmedes et al., 2013; Crempien and Archuleta, 2015) to produce "scenario" ground motions for analysis, and (ii) uses DRM to input these seismic motions to a model of site and structure. The method is applied to a simple site model which include buildings with different dynamic and geometric properties on the free surface. The structural response and performance metrics such as interstory drift-ratio, maximum floor accelerations, etc., are compared with current modeling strategies.

Keywords: Soil-Structure Interaction, Finite-fault Kinematic Ruptures, Domain Reduction Method.

1. Introduction

To this date, earthquake-soil-structure interaction (ESSI) studies have focused on modeling the near surface geology and behavior of soil with great detail (e.g. [1], [2]), but have assumed that the input earthquake motions are planar incident waves computed from recorded ground motions. The input ground motion is obtained, usually, by deconvolving recorded motions in depth to compute a "within" motion which is applied as a stress boundary condition at the bottom of the model[cite Borja]. This method of seismic wave input is termed the "1-D site assumption" herein and is extendable to all three components of recorded motions. The 1-D site assumption is a pervasive one throughout earthquake engineering, especially when soil-structure interaction effects are to be included. Nevertheless, this assumption is ultimately unphysical as it neglects important aspects of the wave propagation phenomena as observed my seismology.

Ideally, a complete ESSI model should include: (a) physical model of the source rupture process, (b) propagation of waves through the heterogeneous crust, (c) nonlinear site response, and (d) a detailed structural model of the infrastructure of interest. The domain reduction method [4] (DRM) reduces the computational demand of this task by replacing the wave propagation inside the crust to only a small neighborhood of interest around the structure, by applying forces at a boundary such that the displacement produced are compatible with those predicted by wave propagation models of the "free field" problem. These forces are computed from the predicted earthquake wave field, which can be obtained using any method that solves the elastic-wave equation.

The DRM is the first method fully capable of exciting a finite-element model of local site and structure, in a way which is compatible with observed seismic wave propagation features. In other words, using the DRM it is possible to avoid the 1-D site assumption altogether. Despite being around for more than 13 years, its adoption by both researchers and practitioners of earthquake engineering has been scarce to say the least. The reason behind this is twofold: first it requires a detailed knowledge of the wave-field around the site of interest, which in turn requires complex and expensive seismological simulations; and, second, any practically sized model would require large amounts of data storage just for the DRM waveforms. This "big data" must be accessed efficiently to avoid bottleneck the simulations.

The use of high-performance computing techniques, which exploit machine parallelism, along with other technological advancements, such as fast solid-state drives, has made this procedure feasible for analysis on personal computers. Fairly complex, nonlinear dynamic models of site and structure can be solved within the constraints of contemporary high-end personal machines. Even larger, more complex, models can be solved if an HPC cluster or HPC "cloud resources" are used. The RealESSI simulator [5] developed by the CompGeoMech group at UC Davis, provides a scalable, high-performance finite element modeling and simulation platform facilitating the use of the DRM in earthquake engineering. RealESSI uses a specialized input format, based on the HDF5 library, to store DRM motions and provide fast and scalable parallel access to DRM datasets.

With this infrastructure in place, it is possible to carry out time-domain simulations where attention is payed to all aspects of the problem: earthquake rupture, elastic seismic wave propagation in the crust, local site response and structural response. This is the ultimate way to model an earthquake-soil-structure interaction problem and minimizing unphysical assumptions.

A method is presented which uses the UCSB broadband ground motion simulation method [6, 7] to produce "scenario" ground motions for analysis of nonlinear dynamic finite element models of site and structure using the DRM. The methodology is illustrated with a simple case for a realistic structure of interest.

Figure 1 shows a flowchart that illustrates the steps in the method. It starts with the provision of earthquake scenario, modeling the wave propagation from source to DRM boundary and then simulating the site and structure response with finite elements.

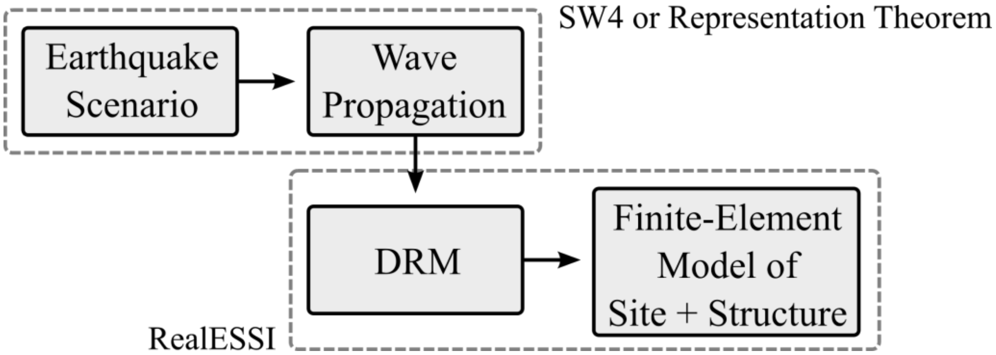

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Figure 1. The proposed method uses the DRM as cornerstone to couple seismic simulations with finite-element models of local site and structure, providing a physically complete modeling framework for ESSI.

2. Specifying Earthquake Scenarios with the UCSB Method

The specification of an earthquake scenario involves providing a model of rupture on a fault which is used to compute seismic wave propagation through the crust modeled. There are several approaches to simulate wave propagation in a visco-elastic medium, and into the site boundary. A kinematic earthquake rupture model, the approach proposed herein, would prescribe rupture propagation on each point on the fault by assuming an evolution of the rupture process. Such an assumption should be based on physical properties of past observed events for the considered fault.

A kinematic source scenario would start by assuming that the event occurs on a known fault, that is, the geometry and event history is known to a reasonable extent. Then, an event magnitude (say for a design basis earthquake or a maximum credible earthquake as defined from a previous seismic hazard assessment) is chosen. From the event magnitude, fault extents and geometry are chosen based on a scaling relationship for the fault. From magnitude and extents the maximum implied average slip over the fault is determined. Then an adequate discretization of the fault is provided. Several slip distributions might be chosen at this point depending on the faulting style and previous history of the fault. These might be used to provide different scenarios (all with same magnitude and overall geometry) which emphasize different effects like presence or absence of forward directivity pulses.

The UCSB method [6, 7] for seismic source representation and simulation is endorsed herein and summarized below.

1. With a specified earthquake seismic moment (or magnitude) and stress drop, the corner frequency is determined for the entire event.

2. A kinematic rupture model is synthesized such that it satisfies 1-point statistics for each parameter that represents the slip-rate function at each point on the fault (slip, peak-time, rise-time and rupture velocity). The correlations between the four source parameters on the fault must be consistent with the results of [7]. The correlated synthetic realizations of the random fields are generated with the NORmal To Anything (NORTA) method [8].

3. Once the random fields of each slip-rate parameter have been computed, the final slip on the fault is scaled simultaneously with the rise-time to match the target seismic moment and a ω-squared spectrum [9].

4. Once the kinematic source model is ready, an appropriate method is used to compute motions at the DRM boundaries.

Figure 2 shows an earthquake scenario assumed for the thrust San Ramon fault located in eastern Santiago, Chile. For each scenario, we randomize the seismic moment on the fault, the rupture initiation points (which is shown as green stars) and the rupture initiation at each point of the fault.

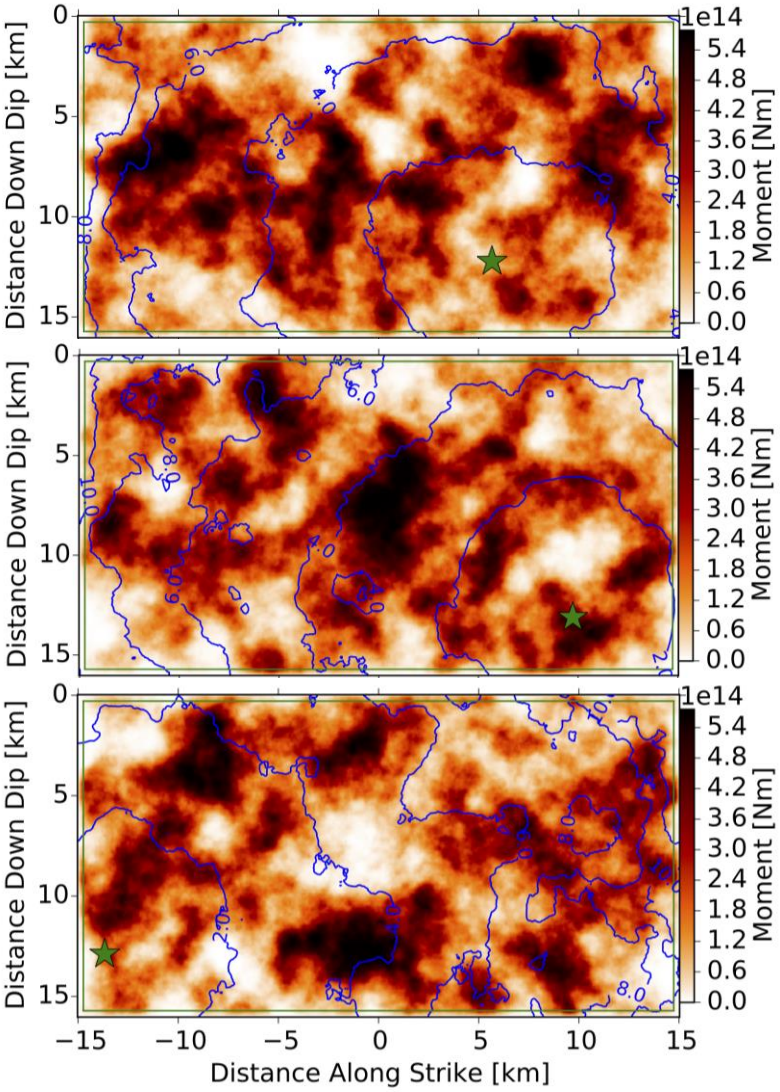

Figure 2. We show three stochastic realizations of earthquake rupture on a 30 km length and 16 km wide fault that represents the possible rupture scenarios of a Mw 6.9 earthquake on the San Ramon Fault. The green star is the rupture initiation point, the rupture initiation times are given by the blue contour lines and the maps show seismic moment at each point on the fault.

For the last step of the specification of the earthquake scenario, an appropriate model of crustal velocity structure and density is needed with which to compute the seismic wave propagation due to the specified scenario. The most basic model which can still yield credible results is a layered half-space model. This kind of models have the advantage that can be solved without extensive computational resources by using the frequency-wavenumber family of methods [10]. If a 3-D crustal structure is available, the elastodynamic equations must be solved by a 3-D numerical method such as finite-differences or finite elements.

3. Local Soil-Structure Interaction Model with DRM

With the ability to obtain a solution to the wave-equation due to an earthquake scenario at any given point in space, it becomes possible to employ the DRM to input these waves in a consistent manner. Figure 3 shows a schematic representation of the DRM. A single layer of elements encompassing the site and structure is chosen and the ground motion due to the event is computed the the nodes of this layer. Internal nodes are labeled ‘b’ for boundary nodes (in red) while exterior nodes are labeled ‘e’.

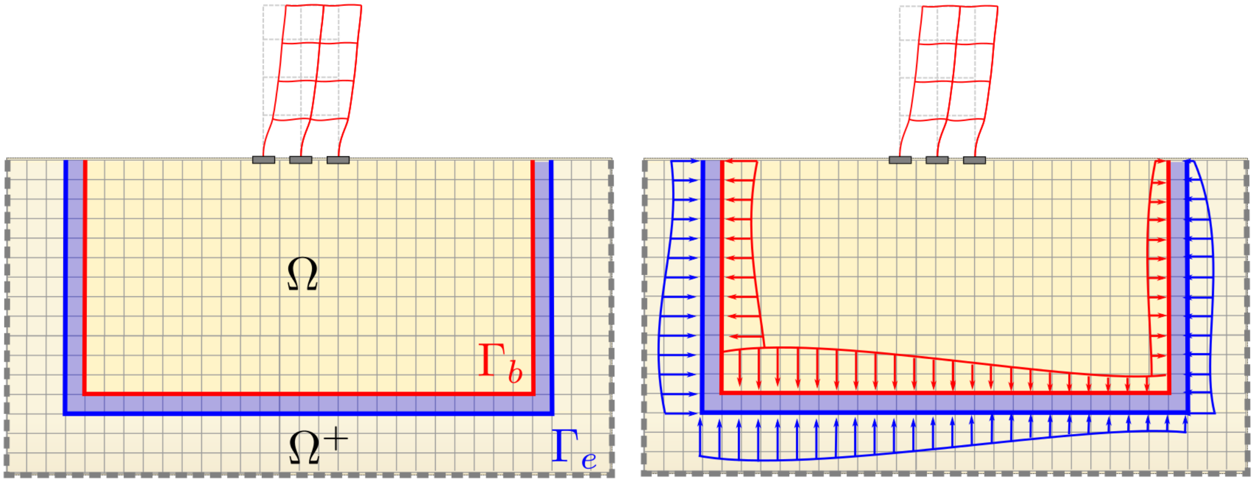

Figure 3. The DRM solves the problem of seismic wave propagation inside a reduced domain by replacing the previously known motion at the nodes of a layer of elements surrounding the domain by a set of equivalent forces.

In this study, a reference model for a nuclear power plant containment building, auxiliary building and foundation is used. The model rests on a 100m x 100m 3.5m thick foundation slab, has a 20m radius containment dome over a 40m high containment cylinder, its thickness is 1.6m. Auxiliary building consists of 5 stories, and is composed of a regular grid of shear walls spaced every 12.5 m and with 0.4m thickness in the interior walls and 1.6m thickness in the exterior walls. Ceiling slabs are 0.6m thick at all levels except the top where they are 1.0m thick.

The DRM layer of elements is placed at a distance of 30m from the edge of the foundation. Its thickness is one element in size, which is 2.5m. The element spacing is chosen such that a maximum frequency greater than 10 Hz is resolvable at a shear wave speed $V_s = 500m/s$.

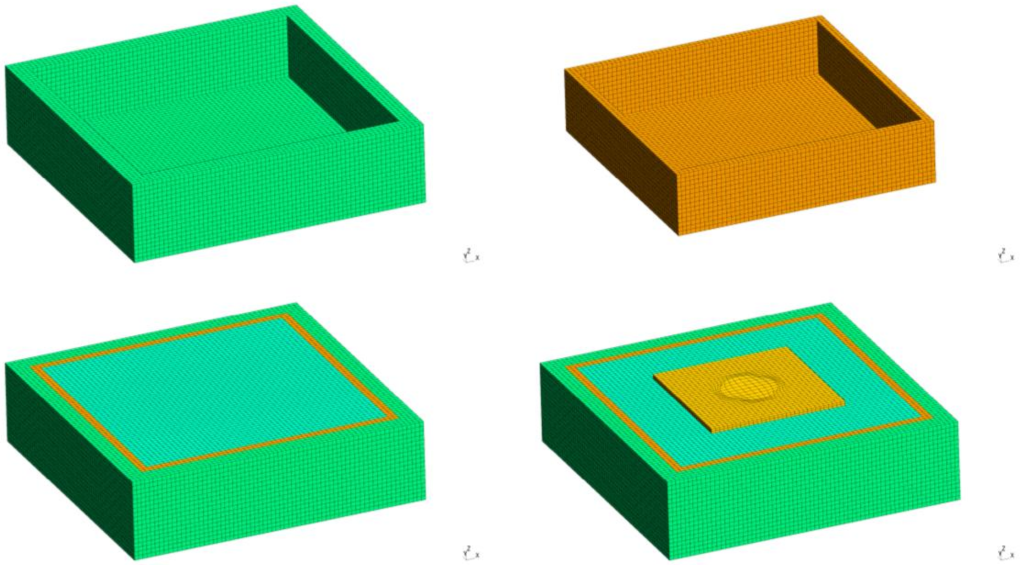

Figure 4. The DRM layer is placed at a distance of 30m from the edge of the foundation slab. An extra layer of 5 elements is placed after the DRM layer to absorb out-going waves arising from the radiation damping of the structure.

Solid elements are used to model both the DRM layer,absorbing elements and the foundation site and foundation slab. Absorption, DRM and foundation slab elements use an isotropic-elastic constitutive law, while the soil elements have a non-linear Drucker-Prager plasticity model with Armstrong-Frederick kinematic hardening. The cyclic response of the soil constitutive model is shown in Figure 5.

Low strain properties are chosen to match the site shear and compressive wave velocities and its density. Additional Rayleigh damping is used throughout the model. The damping is set to 2% at soil elements for frequencies of 0.5 Hz and 5Hz and at 20% for the absorption elements.

Figure 6 shows the complete model for the nuclear power plant. Containment and auxiliary buildings are modeled using shell elements with 6 degrees-of-freedom per node (3 displacements and 3 rotations) using an elastic-isotropic constitutive law. Shells are partially embedded into the foundation slab to model out-of-plane rigidity at the connection between bricks (3 degrees-of-freedom per node) with the shells.

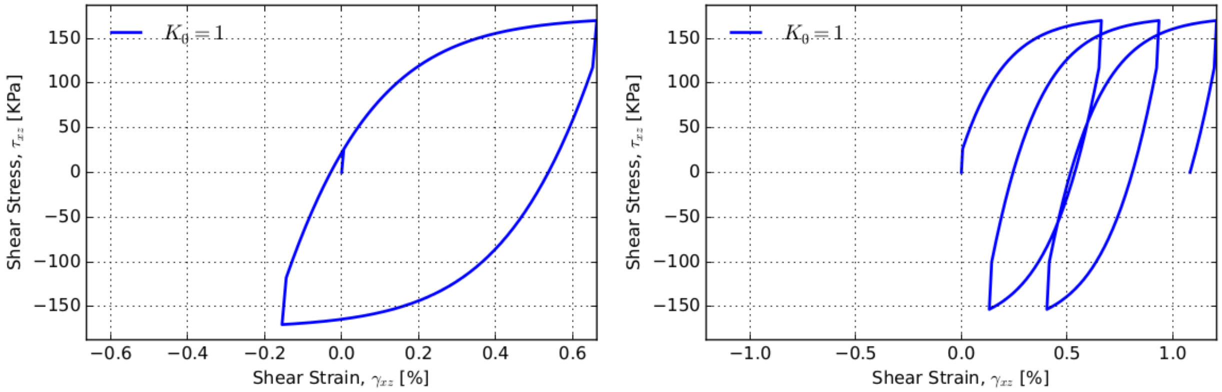

Figure 5. Cyclic response of the chosen material model with symmetric and unsymmetric loading conditions.

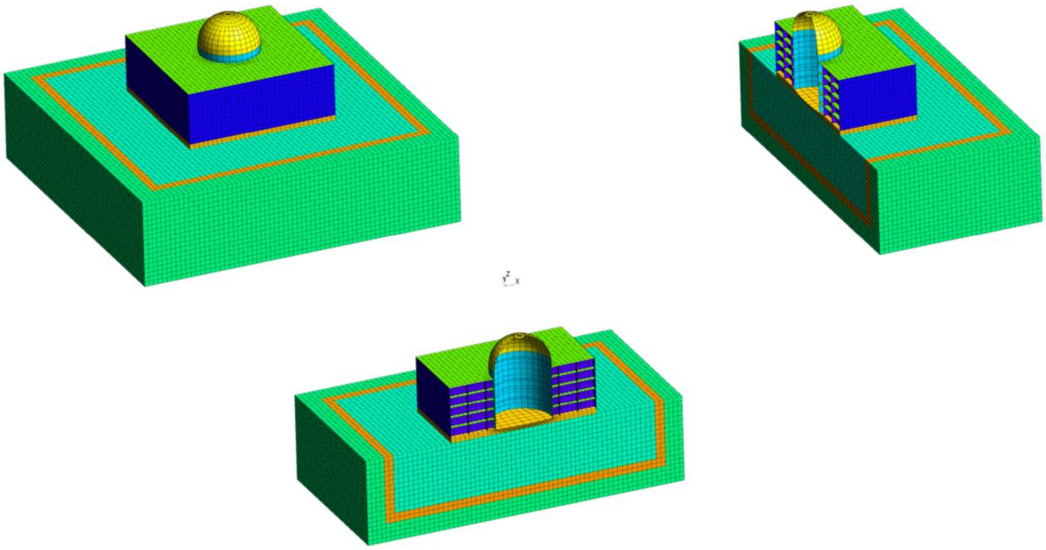

Figure 6. Finite-element mesh of the complete nuclear power plant model showing containment building and auxiliary building in context with the layer of DRM elements and absorption elements.

The resulting mesh consists in 106,165 nodes, of which 9,728 define 6 degrees-of-freedom (three translations and three rotations) and 96,437 define 3 degrees-of-freedom. A total of 100,736 elements are defined, consisting of 31,824 shells and (68,912) eight-node bricks. 37,632 of the continuum elements contain non-linear material representing the soil, while the rest use linear materials representing the DRM layer, absorption layer and foundation slab. This results in 551,296 Gauss integration points of which 301,056 are non-linear material points.

An explicit (forward Euler) method is used for constitutive integration. Dynamic solution is advanced by using Newmark's method with standard parameters.

4. Input Motions

To illustrate the concept of ESSI analysis with earthquake scenario specification, we will generate motions for a simple case of a layered half-space crustal model with a point source motion. Figure 7 shows the setup of the seismological problem. The earthquake is modeled as a dip-slip double-couple point source and is located 2.5 km away from the site of the nuclear power plant. Source time function is a brune source with corner frequency $f_0 = 8Hz$.

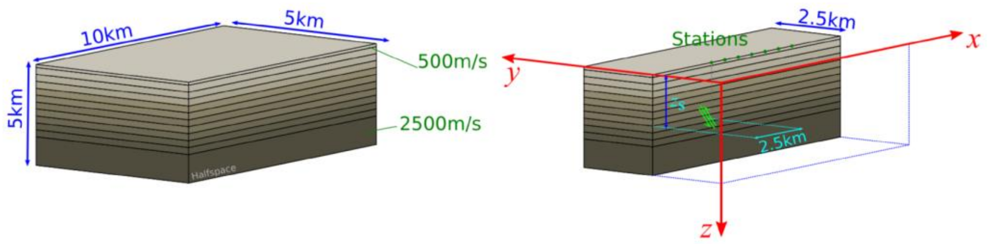

Figure 7. Setup of the geology for this study.

Elastodynamic equations are solved within a 10x5x5 km block discretized every 5m (to achieve a maximum resolvable frequency of 10Hz). The SW4 program [11] (Seismic Wave 4th Order, a parallel scalable 4th order finite difference seismic simulation program developed at Lawrence Livermore National Labs) is used to simulate this case, generating DRM input motions for the problem, and is run using the ESSI HPC cluster at the University of California, Davis.

Figure 8 shows the displacement and acceleration traces generated at the place of the site of the NPP.

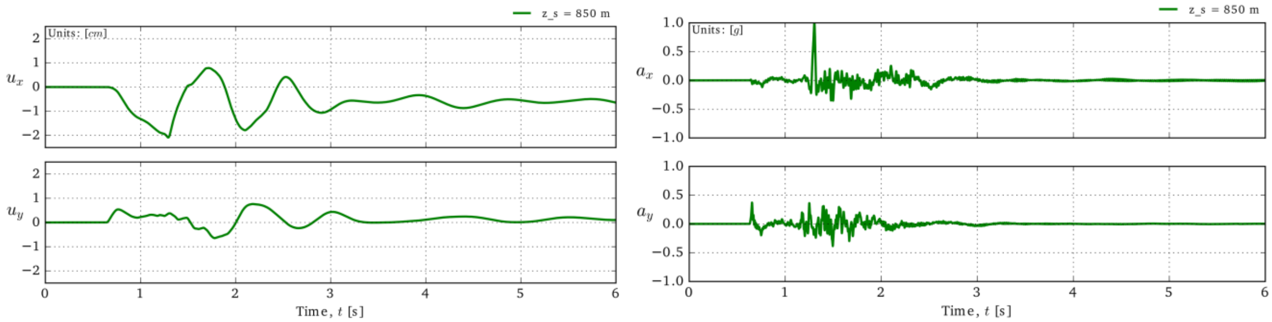

Figure 8. Displacement and acceleration traces in X and Z directions due to the point source. Traces are scaled to achieve a 1g horizontal acceleration at the site.

Finally, the motion recorded at the middle of the site were deconvolved in depth using the program "Shake91" to obtain within motions at the depth of the nodes in the DRM layer. With this, a 1-D equivalent wave field was obtained and input into the model using the DRM. All 3 components were de-convolved in the same manner by adjusting the site properties accordingly. Two horizontal components used the shear wave propagation speed, while the vertical component used the propagation speed of compression waves. It is very important to stress that the deconvolution process matches the recorded motion (due to 3-D wave field) perfectly in all components.

The damping was set to 2% critical in the deconvolution process. This damping was matched in the full model using Rayleigh damping as explained before.

An important aspect of performing DRM analysis is checking whether the free field site, that is, the finite element model not considering the superstructure, reproduces the observed recorded motions at the site. For both the deconvolved 1-D equivalent and the full 3-D wave fields it was found that this was the case. As a word of caution to future analysts, this is not a trivial and very important check.

The full DRM datasets stored in the HDF5 format produced about 3GB of data for this case.

5. Results and Discussion

Figure 9 shows the simulated accelerations at different places of the NPP model due to both the equivalent 1-D wave field obtained by deconvolution of recorded motions and also the one obtained using a fully 3-D input wave field. Again, both motions were input into the model using the DRM.

Shown are the accelerations response at the top of containment, top of foundation slab and south-west corner of the auxilliary building.

It is notable that even though the de-convolution process is able to match observed site response perfectly, when this is input into a model there are differences in the response when compared to a fully 3-D analysis. In this case, the geology and faulting mechanism still favors the use of 1-D analysis, although deviations start to appear.

It is expected that at higher frequency contents, using 3-D crustal geologies, and lower shear wave speeds these differences become greater. Though doing so requires greater computational power than the one used herein.

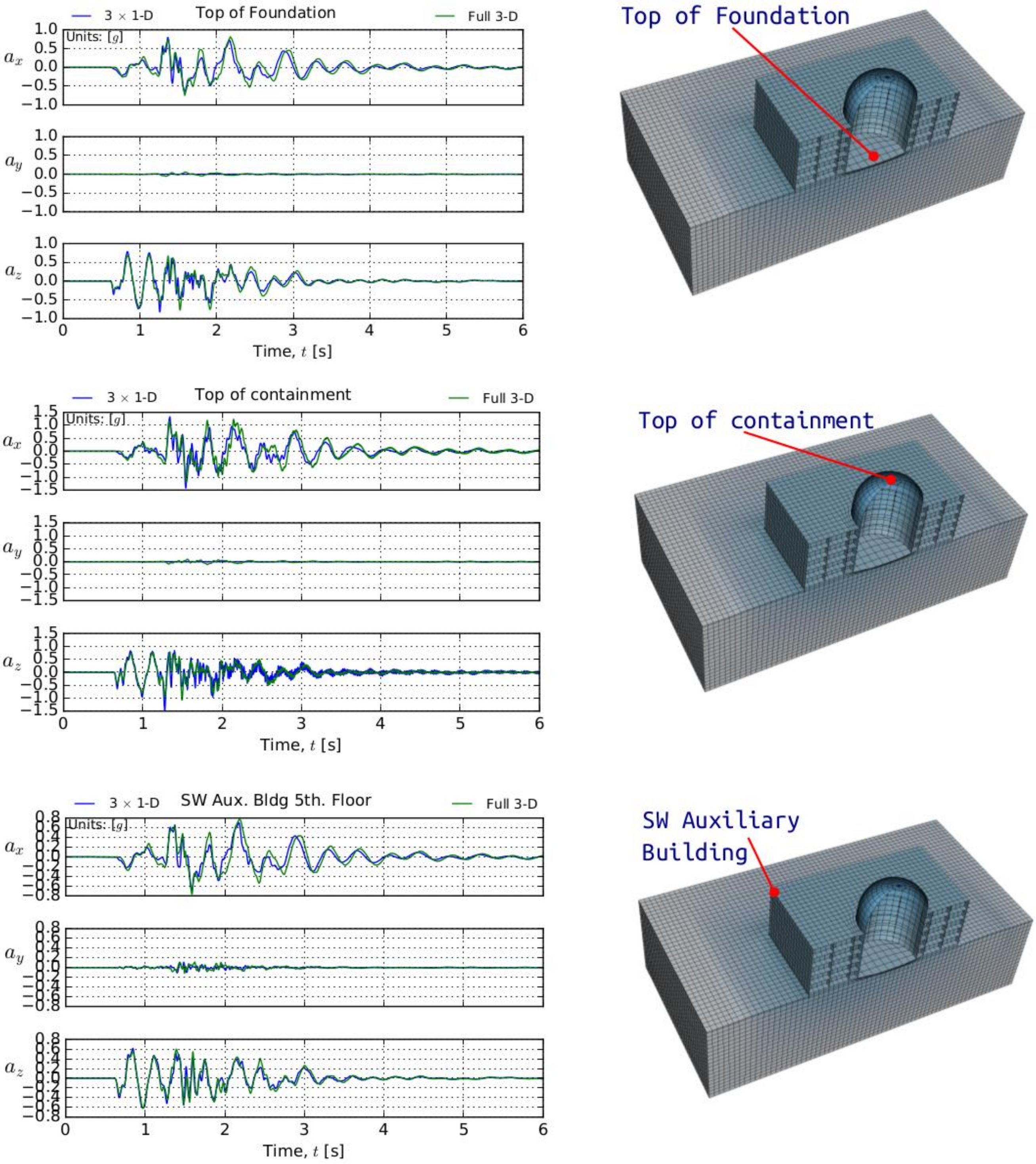

Figure 9. Motions simulated at different points in the structure.

6. Conclusions

A case is made that it is now feasible to have a physical model which encompasses the earthquake source, the path propagation and the site, while accounting for all source and site effects, including non-linear ones. The UCSB method is proposed as the preferred methodoogy to produce realistic input motions for the DRM. The feasibility of the method is shown using a simpler case involving a point source generating seismic waves in a heterogeneous, layered space. The motions produced by that case were input into a nonlinear model of site and soil using the domain reduction method. Results were compared with the case when the input wave field is assumed 1-D but equivalent to the recorded (simulated) motions, by deconvolving in depth. This last step represents standard state-of-practise for soil-structure interaction studies.

Apart from demonstrating the feasibility of the approach, a point is made that this more physical approach yields results which are different than those which assume wave-field unidimensionality. It is postulated that these differences can only worsen when more complex earthquake, path and site conditions are considered.

7. References

[1] Z. Yang, B. Jeremić. Study of Soil Layering Effects on Lateral Loading Behavior of Piles *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, Volume 131, No. 6, June 2005, pp. 762-770.

[2] B. Jeremic, S. Kunnath, F. Xiong. Influence of Soil-Structure interaction of seismic response of bridges. *International Journal of Engineering Structures*. Volume 26, Issue 3, Feb 20054, pp 391-402

[3] J. A. Abell (2016): Earthquake-Soil-Structure Interaction Modeling of Nuclear Power Plants for Near-Field Events, PhD Dissertation, Dept. of Civil & Environmental Engineering, University of California, Davis.

[4] J. Bielak, K. Loukakis, Y. Hisada, and C. Yoshimura, Domain Reduction Method for Three--Dimensional Earthquake Modeling in Localized Regions. Part {I}: Theory, *Bull. Seismol. Soc. Am.*, vol. 93, no. 2, pp. 817–824,2003.

[5] N. Tafazzoli, F. Pisanò, J. A. Abell M., B. Kamrani, C.-G. Jeong, B. Aldridge, R. Roche, A. Kammerer, and B. Jeremic- ESSI Simulator Program, Current Status . *Proceedings of the 22nd. Structural Mechanics in Reactor Technology (SMiRT 22) Conference*, San Francisco, California, U.S.A

[6] Crempien, J. G., and Archuleta, R. J. (2015). UCSB Method for Simulation of Broadband Ground Motion from Kinematic Earthquake Sources. *Seismological Research Letters*, *86*(1), 61-67.

[7] Schmedes, J., R. J. Archuleta, and D. Lavallée (2010): Correlation of earthquake source parameters inferred from dynamic rupture simulations, *J. Geophys. Res.*, **115**, B03304, doi:10.1029/2009JB006689.

[8] Cario, M. C., & Nelson, B. L. (1997). *Modeling and generating random vectors with arbitrary marginal distributions and correlation matrix*. Technical Report, Department of Industrial Engineering and Management Sciences, Northwestern University, Evanston, Illinois.

[9] Liu, P., Archuleta, R. J., & Hartzell, S. H. (2006). Prediction of broadband ground-motion time histories: Hybrid low/high-frequency method with correlated random source parameters. *Bulletin of the Seismological Society of America*, *96*(6), 2118-2130.

[10] Zhu, L., & Rivera, L. A. (2002). A note on the dynamic and static displacements from a point source in multilayered media. *Geophysical Journal International*, *148*(3), 619-627.

[11] N. A. Petersson and B. Sjogreen (2014): Super-grid Modeling of the Elastic Wave Equation in Semi-bounded Domains. *Communications in Computational Physics* 16(4):913-955.